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An Interim Report on the Investigations Carried out to 31 August 1985

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INVESTIGATION OF PELLET ACCELERATION BY AN ARC HEATED GAS GUN*
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S.A. Andersen, J. Bundgaard, V.O. Jensen, A. Nordskov, B. Sass, H. Sørensen, and K.-V. Weisberg

Abstract. Deep penetration of pellets into the JET plasma may prove to be a useful tool for density and profile control. In JET deep penetration will require pellet velocities and sizes above those obtained so far. An experimental setup designed for a study of acceleration of 3 mm$^{\emptyset}$ pellets by an arc heated gas gun is described. The aim of the work is to obtain pellet velocities well above 2 km/s. To obtain this aim will require a much more powerful power unit than the one that was available for the present work. Only a few results, obtained mostly during testing of the various parts of the setup, are presented. Although the obtained velocities are low (~ 1500 m/s) the results are encouraging because they demonstrate that pellets can stand a high acceleration pressure without disintegrating. With a suitable power supply which can maintain this high acceleration pressure as the pellet moves all the way through the barrel, velocities above 2 km/s would certainly be expected.

* This work was done under Art.-14 contract No. JR4/9006 between the JET Joint Undertaking and the Fusion Research Unit of the Association Euratom-Risø National Laboratory.

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I. INTRODUCTION

I.1. Pellet injection into fusion experiments

The idea of using pellet injection for refuelling and also for diagnosing the plasma in fusion devices was first discussed by Rose[1] in 1969. Two review articles describing the early work in this field were published around 1980 by Chang et al.[2] and by Milora[3]. Recently the interest in pellet injection has grown strongly, partly because of the rapid development in the performance of pellet injector systems, and partly because of the interesting results obtained when using injected pellets in fusion experiments.

The development of injector systems has followed two lines: centrifugal injectors and pneumatic injectors (gas gun injectors). The main part of the development work on centrifugal injectors is done at IPP, Garching[4] and at ORNL, Oak Ridge[5].

Centrifugal injectors have the two main advantages:

a) there is no propellent gas flowing behind the pellet, which has to be removed by a differential pumping system,

b) they can deliver pellets continuously for some time up to a rate given by the rotation frequency of the centrifuge. (40 pellets pr. second were used by the ORNL team working at the D-III device at GA[6]).

Their disadvantages are:

a) centrifugal injectors have inherently a severe limitation in pellet velocity of around 1.5 - 2 km/s (the present record is however about 800 m/s and is held by the ORNL team),

b) the angular scatter of the pellet trajectories is as high as ~ 1°.

Pneumatic injectors on the other hand have the following advantages:

a) There is no inherent limitation to the pellet velocity. The fact that the sound velocity in the propellent gas is an upper limit to the pellet velocity calls for high temperature in the propellent. Simple gas gun systems, where the propellent gas is applied to the pellet through a fast, high pressure valve have - among at other places - been developed at IPP, Garching[7], at Risø[8], and at ORNL[5], and they have obtained pellet velocities of around 1.5 km/s.

   In order to obtain higher velocities, various ways of increasing and shaping the pressure pulse of the propellent gas have been suggested. There are reasons to believe that further developments on pneumatic injectors will increase the obtainable pellet velocity to values well above 2 km/s.

b) The angular scatter of the pellet trajectories may be as low as $\pm 0.05^{o}$.

The most severe disadvantages with pneumatic injectors are:

a) Repetitive operation appears to be more difficult than with the centrifugal injectors. A pneumatic system, which can deliver 7 pellets successively into the TFTR plasma was, however, successfully designed at ORNL[5].

b) The propellent gas, having a mass comparable to that of the pellet, has to be pumped away before entering the plasma chamber.

Encouraging results from pellet injection into fusion devices have recently been obtained. At the IAEA conference in London in 1984 results were reported from pellet injection into Doublet III, Alcator C, ISX-B, and TFR. Foster[6] reported a significantly improved energy confinement time obtained with multipellet injection into the Doublet III device from a centrifugal injector. A Lawson parameter record of $n\tau_E$ = $0.6\text{-}0.8\times10^{14}$ s·cm^{-3} was obtained in Alcator C with the injection of up to four pellets from a pneumatic injector[9]. Pellet injection from a four pellet pneumatic injector was also used in ISX-B[10] to study density control with pumped limiters. At TFR, injection of single pellets from a Risø pneumatic gun was used to study radial transport[11]. More recently and after the IAEA London conference further investigations with pellet injection used either for fuelling/refuelling or for diagnostic purposes have been reported[12,13,14].

One of the main problems encountered in pellet injection experiments is caused by a high ablation rate for pellets in hot plasmas. Because of this fast ablation rate, high injection velocities are required in order to reach appreciable penetration depths. Various theoretical models for pellet ablation have been proposed and discussed. Based on some experimental results the "neutral shielding model" proposed by Milora and Foster[2,3] is now believed to describe adequately the pellet ablation rate at least in low and medium temperature Maxwellian plasmas. The model predicts that the pellet velocity required to penetrate a distance δ into a homogeneous plasma with density n_e and temperature T_e is[15]

$$v_p \propto \delta r_p^{-5/3} M^{-1/3} n_e^{1/3} T_e^{11/6} ,$$

where r_p is the pellet radius and M the mass number of the plasma ions. When evaluated for JET parameters one finds that "deep pellet penetration" (i.e. $\delta \sim a$) in JET would require pellets of 4-6 mm diameter injected at velocities in the range 2-10 km/s.

It is clear that for pellets used for diagnostic purposes a deep penetration depth is desirable. As far as pellets for fuelling are concerned, arguments have been raised that penetration depths of only a fraction of the minor radius are needed[16]. The situation concerning the need for deep penetration of fuelling pellets is, however, unclear at this stage. JET has therefore adopted a strategy, that they want to have available an injector system capable of injecting pellets penetrating up to all radii.

I.2. Background for and description of work programme

The Fusion Research Unit at Risø National Laboratory has worked on the development of pneumatic pellet injectors for a couple of years. A few years ago we became interested in trying to accelerate pellets up to velocities above the 1.5-2 km/s obtainable with normal gas gun systems. The higher velocities should be obtainable by arc heating the propellent gas behind the pellet. Preliminary experiments had indicated that this method might be useful. The Risø group therefore suggested to JET to undertake an Art-14 study for JET aimed at accelerating large (~ 3 mm$^{\varnothing}$), single deuterium pellets to as high a velocity as possible by means of an arc heated propellent gas. The JET director accepted the proposal and a contract was signed in July 1984. According to the contract this work period should be terminated and a draft report written by September 1st 1985.

A simple gas gun accelerator is shown schematically in Fig. I.1. It is generally accepted that there are three factors that limit the velocity to around 1.5 km/s as encountered with such systems:

a) The pellet can stand only a certain acceleration due to pressure before breaking. There are indications that a pellet in a barrel can stand at least 25×10^{5} Nm^{-2} although the tensile strength of frozen hydrogen is only around 5×10^{5} Nm^{-2}.

b) The speed of sound in the driver gas ($v_s = (\gamma\kappa T/m)^{1/2} \approx 1.3$ km/s) puts an upper limit to the rate of energy transmission to the pellet through the gas. Furthermore, as the pellet moves along through the barrel it appears to be impossible to maintain the high accelerating pressure; the rapid expansion of the propellent gas cannot be compensated by fresh gas streaming in from the reservoir.

The idea behind the Risø proposal for obtaining higher pellet velocities was to overcome the limiting factors by replacing the fast valve and the high pressure gas reservoir by a discharge chamber. A thin film of solid H_2 is condensed on the inner wall of the discharge chamber. When a pellet is to be accelerated a discharge is created between a central electrode and the chamber wall. This discharge rapidly heats up and vapourizes the hydrogen on the walls and thereby forms a high-pressure, hot, propellent gas acting on the pellet. By controlling the discharge it should be possible to approach a constant pressure acting on the pellet as it moves along the barrel. During the acceleration phase this pressure should be kept constant and as close as possible to the maximum pressure the pellet can stand [constant pressure gun].

During the negotiations of the programme for the work under contract it was agreed that "the objective of this work is the investigation of the acceleration of deuterium pellets ca. 3 mm in diameter towards achieving pellet velocities clearly in excess of 2 km/s and exploiting the limits of the arc heated gas gun to obtain design parameters for a possible pellet injection into JET".

To assess the requirements for the power unit for the arc we assumed that we are to accelerate a cylindrical deuterium pellet (3.5-4 mm long and 3 mm in diameter) by a constant pressure of $2.5 \cdot 10^6$ Nm^{-2} through a 1 m long barrel. The mass of the pellet is around 5 mg and it is acted upon by a force close to 20 N, corresponding to an acceleration of some $4 \cdot 10^6$ ms^{-2}. The pellet velocity of $3 \cdot 10^3$ ms^{-1} is then obtained after 0.75 ms of acceleration. After this time interval the kinetic energy of the pellet is of the order of 20 J.

It was decided to design a power supply unit which also should be able to accelerate pellets, 8 times as large, to velocities approaching 10^4 ms^{-1} i.e. to energies around 1 kJ. Assuming various efficiencies leads to the requirement that the power supply should be able to deliver 20 kJ within 0.5-1 ms and the shape of the delivered power profile within the 0.5-1 ms should be controllable within certain limits.

It was agreed and included in the contract that the power supply should be designed and built in such a way that it also could be used later for accelerating pellets into JET, hence the high performance requirements mentioned above. The design work should be performed as a part of the contract, but JET would order and purchase the power unit from a manufacturer and put it at Risø's disposal for the work. A power unit meeting the requirements was designed in collaboration with a local manufacturer as part of the contract work. Partly due to a long delivery time from the manufacturer JET decided to redesign the power unit and to have it built by another manufacturer. As the design and the delivery of the power unit took much longer than originally planned (the unit was not delivered to Risø by the end of August 1985) it was decided at Risø to construct a smaller power unit (~ 1 kJ) in order to begin work and to test various subsystems.

In order to achieve the optimum discharge conditions good monitoring of the pellet position and of the pressure acting on it, as it moves through the barrel, is required. It is also necessary to measure its velocity, its mass and its momentum outside the barrel. Diagnostics for all these purposes were designed and built. They were first tested using pellets accelerated by a conventional fast valve gas gun. Later a few runs were made accelerating the pellets by a discharge pressure, obtained using the small power unit.

The present report describes the work completed by the end of July 1985. The mechanical setup in which the pellets are made and accelerated is described in chapter II. A number of diagnostics for studying the accelerated pellets both inside and outside the gun barrel are discussed in chapter III.

Chapter IV outlines the automatic firing system and the data collection system. In chapters V and VI we present the preliminary results obtained so far. Finally chapter VII contains conclusions and some suggestions for further work.

II. THE SETUP

The setup consists of the cryogenic part where the pellets are made and accelerated and the outer vacuum system where the pellets are studied. All this will be discussed in the present chapter.

The methods used for making the pellet are the same as those described earlier for smaller pellets[8,17,18], these shall be described here only very briefly. A cylinder is placed below the base of a liquid helium cryostat as shown in Fig. II.1 and in more detail in Fig. II.2. The cylinder is filled with solid D_2. By applying a force on the piston the deuterium is extruded through a nozzle when the cylinder and the nozzle are heated to suitable temperatures (somewhere between 7 and 10 K). The filament of extruded D_2 crosses a channel to which the gun barrel is attached. The gun barrel consists of two parts, the rear, which is fixed, and the front, which is moveable along its axis. When the front part is pushed backwards a pellet is punched out of the filament. The pellet is pushed further backwards and when the two barrels meet, the pellet is deformed and squeezed into the barrel. During this deformation the pellet is elongated by a factor $(d_o/d_i)^2$, where d_o and d_i are the outer and inner diameters of the gun barrel, respectively. This process completed, the gun is now loaded. The dimensions of the pellet thus depend on the barrel diameter and the thickness of the extruded filament.

The gun barrel is made of a commercial stainless steel tube. Only very straight tubes were used; the front barrel and the rear barrel were made of the same tube or of two tubes that agreed in dimensions within a few hundredths of a millimeter. For work with the pneumatic gun, tubes of 4.0 mm o.d. and 3.18 mm i.d. were used. The inner surface of these tubes was not very smooth. For later work with the arc heated gun we obtained tubes with a smooth inner surface; these tubes had an o.d. of 4.0 mm and an i.d. of 3.0 mm.

The pellets are shot out through the gun barrel by means of a burst of high pressure gas. Two methods for applying the high pressure burst behind the pellet have been used. The first method is the one normally used for pneumatic pellet acceleration where hydrogen gas at room temperature is let in through a fast valve. This method is well known at Risø as it was used in all our earlier injector systems[8,11,17,18]. During the work described here this method was mainly used in testing the various diagnostics. The other, is the arc method, previously mentioned, which has the potential to procuce very high pellet velocities and is the subject of this study.

The fast valve for the normal gas gun acceleration is placed in the vacuum right outside the radiation shields as shown in Fig. II.2. A schematic drawing of the fast valve is shown in Fig. II.3. The valve is closed when a plunger with a rubber seal is pressed against the end of a tube, just as in an ordinary valve. The plunger is pulled backwards and the valve is opened when a condenser bank is discharged through the coil. A large amount of high pressure gas is stored in a reservoir surrounding the valve, and this gas will stream out through a straight tube as shown in the drawing. The diameter of the valve opening is 3.5 mm. The gas reservoir is around 200 cm^3 in volume, and it was tested to a pressure of 150 bar. The plunger and the coil, rated for 24 V, are parts from a commercial Skinner valve.

A safety valve is placed just outside the vacuum system. This valve is open for a few seconds just before the fast valve is operated.

The principle for the arc acceleration is shown schematically in Fig. II.4. A discharge chamber is connected to the gun barrel as shown. An amount of hydrogen gas is let into this chamber where it condenses on the inner wall. A coil is wound around the chamber and connected to a central electrode at the end of the chamber. Before firing a shot, the discharge chamber is heated so that the hydrogen pressure inside the chamber increases allowing a discharge to occur between the electrode and the chamber wall, when a voltage is applied. The voltage is applied through the coil; the arc current thus passes through the coil whereby it generates a magnetic field inside the discharge chamber. The energy deposited in the arc creates a high pressure in the discharge chamber by vapourizing and heating the condensed gas. It is this pressure that accelerates the pellet.

The discharge chamber is constructed of stainless steel, both the inner diameter and the inner length are around 20 mm. The central electrode is mounted in a vespel plug as shown in the drawing. The coil is wound on a bobbin placed around the chamber. The chamber, the plug and the bobbin are mounted together in such a manner that the whole setup can be dismounted easily for inspection and repair. The parts are held solidly together as strong forces act on them during a discharge in the arc chamber.

Two power cables for the high voltage, are fed in through the top of the cryostat from where they are led down through the liquid helium and further through the cryostat base by means of ceramic feedthru's (Ceramaseal) that are made for cryogenic work. Below the cryostat base the high voltage cable is connected to the coil while the return cable is connected to the discharge chamber. The discharge chamber is thus the ground reference zero point for the electrical system. A third wire, the potential wire, is connected to the central electrode and led out to room temperature through the vaccum wall to a voltage probe.

It is important that as little heat as possible be conducted to the discharge setup through the electrical wires. Very little heat enters through the power leads because they pass through the liquid helium. One end of the coil is coupled to the liquid helium through the high potential power lead while the other end is coupled to the cryostat base through a thermally conducting saphire piece. The potential wire is made of manganin which has a very low thermal conductivity. During a discharge, energy will be deposited in the arc chamber and in the coil; after a discharge this energy should be carried away as fast as possible and therefore the discharge chamber is strongly thermally coupled to the cryostat base.

It is important that all surfaces reaching high voltages are electrically well insulated. We have seen in earlier work that arcing will occur from a high voltage surface covered by cryo-pumped hydrogen or deuterium. For that reason all high voltage metallic surfaces are very carefully insulated.

The vespel plug in the discharge chamber may be replaced with a plug and a tube connected to the fast valve. This allows testing of the pellet-forming part of the setup with the fast valve system before arc acceleration is attempted.

Outside the cryostat the two power cables are connected to the power supply; the return cable is connected through a shunt by means of which the arc current may be measured.

For the first arc experiments described here, only a small and rather simple power supply unit was used. This unit comprises 4 discharge circuits each containing an ignitron, a 80 μF/2.5 kV capacitor bank and resistors and coils that may be varied as needed for the experiment. The ignitrons are ignited by thyristor circuits that may be fired either by standard 20 V pulses or by TTL signals from for example a CAMAC module. The total energy content of the four circuits is 0.5 kJ at a 2.5 kV charging voltage. The four circuits may be fired in any sequence and the power pulse may be shaped by varying individually the inductance/resistance of each circuit.

This simple power supply will later be replaced with a larger and more powerfull one where the power pulse may be shaped in a more sophisticated way.

Both the fast valve and the arc deliver an amount of propellent gas to inside the vacuum system. This gas should be disposed of in such a manner that it does not diminish the insulating properties of the vacuum around the cryostat. That the gas accompanies the pellet to its destination should also be avoided. Fig. II.5 shows how this problem was solved.

The vacuum system is divided into two parts, the cryogenic vacuum system giving an insulating vacuum for the cryostat, and the outer vacuum system where the propellent gas is disposed of. The two systems are separated by an automatic gate valve, Va 1. The gun barrel ends just in front of the valve plate after having passed through a 20 mm long bore in a plug, Lc 1. There is thus a low conductance between the two vacuum systems. The first part of the outer vacuum system consists of a smaller and a larger chamber of 100 l volume, Vo 1. The outer vacuum system is pumped by a Roots pump of 500 m^3/hour capacity through a tube system of 100 mm i.d. The valve Va 1 is opened just before firing the gun and it is closed again immediately after firing. Most of the propellent gas thus expands into the volume Vo 1 to be pumped away by the Roots pump thereafter, hereby only a small part of the propellent gas leaks backwards into the cryostat vacuum. When the cryostat is cold the backwards leaking gas is cryopumped and only a pressure increase of short duration is seen.

It is also important that the amount of propellent gas accompanying the pellet is minimized. After the volume Vo 1 the pellet passes through a tube Lc 2, 5 mm i.d. and 50 mm length, it passes through a volume Vo 2 of around 6 l, through another tube, Lc 3, of 310 mm length and 14 mm i.d., through a valve, Va 2, and finally it enters a chamber, the ΔP chamber with a volume, ΔVo, of around 40 l. The ΔP chamber is pumped by the Roots pump through a valve, Va 3. By closing the valve, Va 2, immediately after a pellet has passed, one can achieve only a limited amount of the propellent gas accompanying the pellet into the ΔP chamber.

III. DIAGNOSTICS

A number of diagnostic methods are used to study both the acceleration process and the accelerated pellet. The methods are indicated schematically in Fig. III.1. The pressure transient behind the pellet, i.e., the pressure transient from the fast valve or from the arc is measured with a ceramic pressure transducer. The pressure transients in the gun barrel following the passage of the pellet are measured at a number of positions with PCB quartz pressure transducers, while the passage of the pellet through the barrel is followed by means of a number of pellet detectors using optical fibres. Outside the gun barrel the pellet passes through a microwave cavity the output from which is a measure for the pellet mass. Thereafter the pellet passes through three optical pellet detectors, the first two are used for a time of flight measurement while the third one is used to trigger a flash for photographing the pellet. The pellet finally enters the ΔP chamber, here the pellet mass is determined by a measurement of the pressure increase appearing when the pellet vapourizes. In the ΔP chamber the pellet hits a pendulum and from the swing of the pendulum the pellet momentum may be determined.

III.1. The ceramic transducer is made of a circular disc of piezoelectric Lead-Zirconate Titanate, (PZ-transducer). The disc - 1 mm thick, 3 mm diameter - is placed in contact with a 0.2 mm thick membrane in a stainless steel housing. The total length of the probe is 13 mm and the membrane diameter is 4 mm. Special care was taken to obtain a coaxial electrical connection to the piezoelectric disc in order to minimize induction from the time varying magnetic field from the arc chamber coil. The sensitivity of the pressure probe at cryogenic temperatures is ~ 2 mV/bar when it is terminated by 50 nF. The natural frequency is measured to be around 300 kc/s. The pressure probe is attached either to the rear barrel (breech pressure) when used with the fast valve or to the arc chamber when used with the arc.

III.2. The PCB transducer and the optical fibres are attached to the gun barrel together in a connecting block as shown in Fig. III.2. Two optical fibres are connected to each block with standard plugs. They face each other and light is passed from the one to the other through 0.3 mm holes in the gun barrel wall. The PCB pressure transducer may be attached to a block through a holder, or a blinding plug may be attached instead. The pressure transient acts on the pressure transducer through a slit in the barrel wall; the slit width is 0.3 mm and the length 2.5 mm while the transducer membrane diameter is 2.5 mm. Eight such blocks are placed along the 150 cm long gun barrel, one being placed inside the cryogenic radiation shields, the distances between the others increase as we go in the direction of pellet flight. The sensitivity of the PCB transducers is 20 mV/bar and the natural frequency is 250 kc/s.

The fibres used are 0.3 mm quartz fibres. The light sources and the light detectors are placed outside the vacuum system. The fibres are either fed unbroken through the vacuum wall or they are fed through by means of the standard fibre plugs used together with rubber seals.

Three PCB pressure transducers are used; one is cryogenic, i.e.; it may be used down to temperatures of around 76 K. The pressure transducers may be placed in either three of the blocks outside the radiation shields.

III.3. The microwave cavity is shown schematically in Fig. III.3. A microwave circuit for 9 Gc/s is terminated with a tuned cavity. A 5 mm hole is drilled through the center of this cavity; when a pellet passes through this hole the output from the detector will change and this change in electrical signal is proportional to the size of the pellet as described earlier by Jensen et al.[19]. In the present version both the wave guide, 26×13 mm external dimensions, and the cavity are mounted on a vacuum flange. The whole system is placed on a sideflange at the very beginning of volume Vo 2 (Fig. II.5) in such a manner that the hole through the cavity is colinear with the pellet trajectory. The cavity is not an absolut measuring device, here it can be calibrated against the pressure increase in the ΔP chamber, Fig. II.5.

III.4. An optical pellet detector is shown schematically in Fig. III.4. A vacuum chamber with two windows is placed on an optical bench. Here the light from a lamp is collimated by means of two slits and a lens so as to pass through the vacuum chamber as a 10 mm high and 0.3 mm wide light barrier; the light is afterwards focused onto a detector diode by means of another lens. When a pellet passes through the light barrier the light to the detector diode is reduced and the associated electrical signal is amplified by means of a fast amplifier. The output from the amplifier may either be a standard pulse or it may be an analogous signal proportional to the reduction in light intensity. Broken pellets can be detected by means of the analogous signal if the fragments are sufficiently separated. A separation of 2-3 mm is sufficient for fragments moving with velocities of around 1200 m/s.

The detector vacuum chambers are made so that they may be attached to each other. Three detector vacuum chambers are connected to form a part of the volume Vo 2 (Fig. II.5) right after the microwave cavity. The standard pulses from the first two detectors are used for time of flight measurements, the distance between the light barriers being 100 mm. The analogous outputs are combined to be observed as a single trace on a transient recorder.

III.5. Photographying the pellet is performed by means of the third pellet detector which is used to trigger a fast flash. The vacuum chamber used for this detector has windows on all four sides; the light barrier passes through the two side windows as for the normal detectors. The flash is placed below the lower window while the camera is placed above the upper window.

For the first work the flash was a home made one with a flash time of 200 ns. Later the flash used was a Nanolite from Impulsphysik in Hamburg with a flashtime of 20 ns. This flash has a delay time of a few microseconds between the trigger pulse and the light emission. The flash thus has to be displaced correspondingly, in the direction of pellet movement, with respect to the light barrier. The camera is placed above the detector vacuum chamber precisely opposite the flash. The camera used is a Hasselblad camera with motordrive, it is used either with polaroid film or with a fast roll film.

III.6. The ΔP chamber is used to measure the absolute pellet size. As soon as the pellet has entered this chamber the valve, Va 2, (Fig. II.5) is closed. The pressure increase caused by the evaporated pellet is measured with an absolute measuring vacuum meter, a MKS vibrating diaphragm meter with full scale for 1 Torr. The volume of the ΔP chamber is 43.3 l, and a pressure increase of 1.00 Torr at 20 ^{o}C thus corresponds to an amount of gas of 1.43 10^{21} molecules or 9.57 mg. The only problem is to measure the true amount of gas. Some of the gas from the evaporated pellet will leak backwards and some of the propellent gas will enter the ΔP chamber. We attempt to reduce this unwanted gas flow by means of the volumes and tubes shown in Fig. II.5 and by timing the operation of the three automatic valves with respect to the firing. Just before firing valve Va 3 is closed and valve Va 1 is opened. Most of the propellent gas thus expands out into Vo 1 to be pumped by the Roots pump. A fraction of the propellent gas enters Vo 2 through Lc 2. A fraction of this gas will leak into the ΔP chamber through Lc 3. This fraction can be reduced by making Vo 2 larger and by reducing the conductance of Lc 3. Va 1 and Va 2 are both closed just after firing.

III.7. The pendulum is used to measure the momentum of the pellet. When the velocity is known from the time of flight measurement the mass of the pellet may be deduced.

The pendulum is shown schematically in Fig. III.5. It is made of flat lead rings each with an outer diameter of 60 mm and an inner diameter of 20 mm. A number of rings are added together to give a mass of 1.05 kg. The pendulum is hung in a thinwalled monel tube under a NW100 flange, the arm length being 300 mm. The central part of the pendulum, which is hit by the pellet, is exchangeable. A displacement transducer is attached to the monel tube; the output from the transducer is proportional to the pendulum displacement.

The pellet hits the central part of the pendulum which is shaped in such a way as to ensure that as small a part of the pellet momentum as possible is reflected during the impact. Two different shapes for the central part were tested.

The first shape used was conical and upon impact the pellet would slide down the cone. This shape produced results for the pellet mass that were too large. Apparently a large momentum was reflected, either as fragments or as vapor.

The second shape used and inserted in the pendulum is the one shown in Fig. III.5. It is an inverted cone or a funnel that ends with a 2 mm diameter hole. Upon impact the pellet is deformed and slides along the funnel. The deformed pellet passes through the hole and strikes the backplate. The pellet material, small fragments or vapour, can only leave the pendulum sideways and therefore contributes little to the momentum given to the pendulum. After having been used for a few pellets a dent appeared in the center of the backplate, this dent was surrounded by an area with a mat surface, caused by the spray of pellet material.

The pellet masses obtained using the second shape are in fairly good agreement with the results obtained from the ΔP chamber, while the masses obtained by means of the first shape are about 50% too large.

III.8. The arc voltage is that measured between the central electrode and the grounded arc chamber. The measuring wire is led from the central electrode to a voltage probe (1/1000) outside the vacuum chamber. This is done in such a way that induction loops are kept small; induced voltages from the time varying magnetic field associated with the arc chamber coil cannot be measured. The absence of induced voltages in the measuring circuit was checked experimentally; a short-circuit plug was placed in the discharge chamber and the condenser battery was discharged through the arc circuit.

III.9. The arc current is measured either by a 5 mΩ shunt placed in the return wire from the arc circuit to the power supply or later by a current transformer (Pearson Model 301).

IV. AUTOMATIC FIRING SYSTEM AND DATA COLLECTION

IV.1. Automatic firing system. The automatic operation of the gun both for pneumatic and for arc-heated acceleration is performed with a Programable Logic Controller (Electromatic, PLC 230816/PSU 100/616). The operation involves control of 10 electromagnetic valves, 1 electric puncher motor, 4 electrical heaters and signals for triggering of the power supply and the data recording system.

The operation of the gun may be divided into 3 main operations that occur successively: 1) the loading operation, 2) the firing operation and 3) the cooling and refilling operation. The operational details differ for pneumatic and arc-heated acceleration only with respect to the loading and firing operations. With pneumatic acceleration the loading operation involves extrusion of a D_2 filament and punching of a D_2 pellet into the barrel, and the firing operation involves operation of pneumatically actuated vacuum valves and the issuing of trigger pulses to the fast valve power supply and to the data recording system. With arc-heated acceleration the loading operation also involves a restoring compression of the deuterium in the extrusion nozzle prior to the extrusion. This is done in order to regain a compact quality of the deuterium as it is softened by the heat impulse from the previous firing. With arc-heated acceleration the loading operation also includes the inlet of H_2-gas for condensation in the arc-chamber and the firing operation also includes pre-heating of the arc-chamber in order to increase the H_2-gas pressure inside the chamber to a level suitable for arc ignition.

The arc power supply is triggered by a main trigger pulse from the PLC. The subsequent triggering of the power supply batteries is performed by an external timing system. With the interim 4-section 0.5 kJ supply 4 presetable fast timers are used and with the final power supply a programable CAMAC timer system will be used.

The final cooling and refilling operation includes a time interval for cooling of the gun and for refilling of the D_2-extrusion cylinder with a fixed dose of D_2-gas if a lower level of the extrusion piston is reached.

The temperatures in the cryostat are controlled by preset heater on/off-times. The D_2-extrusion process is controlled by establishing a feed-back loop from the piston position through the PLC to the extrusion heaters.

A schematic diagram of the automatic firing system is shown in Fig. IV.1.

IV.2. Data collection. The data collection system is based on a PDP11 mini-computer equipped with a CAMAC crate and an IEEE-488 instrument bus. The computer gathers data from the diagnostic equipment and stores them on floppy disks. It also prints and plots the data on sheets forming an event (pellet shot) entry in the log book.

IV.3. Description of measurements. The data collected can be divided into two types: single data numbers and data arrays of numbers.

Transient waveforms like current, voltage and pressure are digitised in transient recorders which produce data arrays of 4096 numbers, each number representing the signal amplitude at a particular time. The transient recorders are interfaced via the IEEE-488 bus. The other diagnostics produce single data numbers.

Acceleration of the pellet in the barrel is determined by using the time of flight between the fibre optic connector blocks described in chapter III. An octal, CAMAC based, 125 MHz timer, is used for this purpose. The optical signals are detected in two fast detector units designed for the purpose, each containing four channels.

The muzzle speed is determined by means of the time of flight of the pellet between the two light barriers in the optical pellet detectors (see chapter III). In this case the timing is carried out using two Philips timers interfaced via the IEEE-488 bus.

As described in chapter III, the mass of the pellet is measured by 3 independent methods. The microwave cavity produces a short pulse with an amplitude proportional to the mass. This amplitude is digitised by a Wilkinson type ADC, which detects the top and produces a digital output proportional to the peak value. The result is read into the computer via the CAMAC dataway.

The second method of measuring the mass is based on the pendulum. The pendulum transducer mentioned in chapter III produces a slowly rising 3 kc/s signal, which after detection in a synchronous detector is fed to a CAMAC based analog to digital converter. Due to the relatively slow rise of the pendulum signal, the computer is able to detect the peak value by reading the detector signal continuously.

The third method of measuring the mass using the pressure increase in the ΔP chamber is used manually only.

IV.4. Triggering of the data recording system. As mentioned under Sec. IV.1 the data recording system is triggered from the PLC. Although a 2-wire signal the trigger is not a simple pulse but a waveform. The first phase of this waveform is called the "arm time". During this time, the computer arms the transient digitisers and readies the system for the shot. When this time has elapsed, the computer enables the trigger hardware and waits for the shot. The next time the trigger signal goes "active true" defines the time of firing, and duplicates of this signal are distributed by the trigger hardware to the transient digitisers, the octal timer and to the Philips timers, respectively. The time of firing is called "time zero" and is the reference time for digitisers and timers. Later this edge, "time zero", will also be distributed to the arc power supply. The trigger hardware is housed in a CAMAC module.

IV.5. Data storage and presentation. Before each event the computer automatically assigns a number, date and time to it. The event number consists of two parts, a series designator and an event number each consisting of 3 digits. Later this number, along with different file type designators, becomes the file name of disk files.

After the shot the computer gathers data from the diagnostic equipment, computes derived quantities, and stores the data on up to 7 disk files. One of the files is the main file which describes the event and the contents of the other files. The main file is called the "Event Descriptor File" and it has been given the file type of "DES".

The "Event Descriptor File" is written in direct readable form (ASCII characters) which means that it may be printed out without the use of special programmes. The first records identify the file, the generating programme, the project, the event number, and date and time. Next follows a list of single variables with name, type, unit and value, and thereafter 6 "DESCRIPTOR" sections each describing one of the 6 associated data files. The "DESCRIPTOR" sections describe transient recorder data arrays stored in files as raw data to save space. The "DESRIPTOR"s list the file name, the data name, the data set size and type as well as the type, unit and value of the divisions of the axis.

After data storage, the computer starts to print out 3 sheets of information. These sheets are inserted into a log book after the shot. Together with photographs of pellet and ΔP chamber data and other handwritten information, these sheets form the log book entry for the event. The information presented in the sheets is the same as the information stored in the "Event Descriptor File" except for the "DESCRIPTORS". Instead, plots of transient recorder data arrays are given, along with divisions of the axis.

V. RESULTS FOR PNEUMATIC ACCELERATION

Experiments with pneumatic acceleration were performed with two different gun barrels. First with a 950 mm long barrel and later with a barrel of 1450 mm length. The short barrel was used mainly for developing the various diagnostic methods and the number of actual results is limited. The long barrel was used after the diagnostic methods were developed, it was used for testing and calibrating some of these methods and for studying the acceleration itself. Here we first present results obtained with the short barrel, then we present the results of the calibrations and finally we discuss the study of the acceleration.

V.1. Short barrel. The gun was used in connection with development of diagnostic equipment and data handling methods, and no systematic studies were made of the performance of the gun itself. The gun was mostly operated with a propellent gas pressure of 40 bar. With this barrel the gun was very reliable in performance and we shall give some examples.

Earlier experiments with pellets of smaller diameter have shown that the pellets often tumbled, i.e., the angle between the pellet axis and the direction of movement varied from shot to shot and could take any value between 0° and 90°. With this barrel there was no tumbling; this is demonstrated in Fig. V.1. where photographs from one run are shown. During this run 31 shots were fired and photographs of 26 unbroken pellets were obtained. Twenty of the shots were made with the same firing conditions and the standard deviation for the scatter in velocity was 1.6%.

On a later date, 1984.11.22, the microwave cavity was used and for 24 pellets the scatter in the mass measurements was 2%.

On another day the pendulum was tested and for 14 pellets the scatter in response was 3.5% while the scatter in velocity was 0.9%.

A systematic fault existed in the time of flight measurements during these runs and so only the relative values of the velocities were reliable. The highest velocities obtained were about 1300 m/s.

V.2. Long barrel. The long barrel was equipped with detector stations with optical fibres and PCB pressure transducers, and a PZ pressure transducer was mounted between the nozzle and the fast valve. During the first runs with this barrel all the pellets disintegrated and it took several runs altering the conditions such that the pellets remained intact. The reliability never approached that obtained with the short barrel and the pellets again started to tumble.

It is not fully understood why all the pellets broke up in the first runs. When the detector stations were mounted on the barrel, they were thermally coupled to the cryostat base, and it is possible that this coupling was too strong and that it also was unsymmetric. The solid deuterium could therefore have been too cold during the extrusion and the following plastic deformation. This could result in a pellet where the deuterium was not melted together again after the deformation; there would then be internal faults in the pellet and it would easily break into many fragments. After some alterations of the thermal coupling and adjustments of temperatures, unbroken pellets were obtained again.

V.3. Calibration. The long gun barrel was used in connection with a final test of the various diagnostic methods.

As mentioned earlier the pendulum was used with two different shapes of the central part. In the first one the pellet hits a cone and in the second one it hits into a funnel. The first shape with the cone gave results for pellet masses that were too large, while the funnel shape gave results in good agreement with those obtained using the ΔP chamber. The average value of the mass of four pellets obtained with the cone shaped central part was 7.84 mg, while the average value was 5.20 mg for 11 pellets for the funnel shaped central part.

Three different diagnostic methods are available for a measurement of the pellet mass; two of these, the ΔP chamber method and the pendulum method, allow the mass to be deduced directly from the measurement while the third one, the microwave cavity method, requires a calibration by means of one of the other methods. Comparisons between these three methods were made in three runs and the results are shown in table 1 as ratios between the individual mass measurements. For the ΔP chamber and the pendulum the ratios between the deduced masses are given. For the other ratios the results are given in arbitrary units. In all cases the standard deviations for the ratios are given together with the number n of pellets used. Only results for good pellets have been used, i.e., results for pellets that appeared in satisfactory forms on the photographs.

Run	$\frac{m_{pend}}{m_{\Delta P}}$	n	$\frac{m_{m.w.}}{m_{\Delta P}}$	n	$\frac{m_{pend}}{m_{m.w.}}$	n
1985.05.08	0.905±0.021	11	200±8	14	1.83±0.08	11
1985.05.10	0.992±0.076	11	205±11	9	1.97±0.09	16
1985.05.14	-	-	-	-	1.84±0.13	16

Table 1

A number of other tests were made in these runs and the number n of pellets used therefore varies from one group to another.

On 1985.05.08 we tried to reduce the gas flow by inserting various tubes before the ΔP chamber. There was no difference between the results. Therefore we chose to use a limiter tube of 14 mm inner diameter and 310 mm length in all the following runs.

On 1985.05.10 by increasing the power supply energy for the fast valve we tried to increase the amount of propellent gas in the last shots; it was hoped that this would result in a higher velocity. There was no velocity increase but the propellent gas increased to such an amount that the ΔP chamber measurements could no longer be used.

On 1985.05.14 we varied the propellent gas pressure in order to see the variation in velocity. During these measurements we maintained the above mentioned power increase to the fast valve and again the results for the ΔP chamber could not be used.

We see that the standard deviation varies from 2.3% and upwards to around 7.5%. One reason for this variation may be that the pellet quality varies somewhat and that the scatter in quality may vary from one day to another.

The two comparisons between the microwave cavity and the ΔP chamber agree well, while the comparisons in which the pendulum is involved are less satisfactory.

The pellet masses determined with the ΔP chamber are 5.74±0.12 mg from the first run and 5.66±0.31 ms from the second run.

As mentioned earlier we varied the propellent gas pressure in the run on 1985.05.14; we also kept the fast valve open for a longer time and we thus let in more propellent gas. In figure V.2 we show the pellet mass deduced from the pressure increase in the ΔP chamber versus the propellent gas pressure together with the pellet masses deduced in the two previous runs. We see that we get the right masses for the lowest pressure and that the measured mass then increases with increasing pressure.

The velocity and acceleration of the pellet in the barrel are calculated from the arrival times of the pellet at the 8 optical fibre stations placed along the barrel. The distances from the starting point of the pellet to the fibre stations are in mm: station 1) 80, 2) 150, 3) 220, 4) 320, 5) 480, 6) 700, 7) 980, 8) 1320. The final muzzle speed is calculated from time-of-flight at the optical pellet detectors placed 400 mm from the muzzle. A number of runs were performed with different valve pressures. Fig. V.3 shows the muzzle velocity as a function of the propellent gas pressure. It is seen that above approximately 50 bar the velocity levels off. Fig. V.4 shows the pellet arrival time as a function of distance in the barrel. Only the first 7 optical fibre stations were used to obtain this plot. The firing pressure for this shot was 40 bar. Figs. V.5 and V.6 are plots of pellet velocity and acceleration respectively obtained from the data in Fig. V.4.

Fig. V.7 shows the pressure transients as function of time at different positions along the barrel. The upper curve showing the breech pressure at x = -30 mm is obtained from the ceramic PZ transducer placed between the fast valve and the starting position of the pellet. The three lower curves are obtained from PCB pressure transducers. From the foot preceeding the sharp pressure rise, which occurs when the pellet passes the transducer, it is seen that gas travels ahead of the pellet (curves for x = 700 mm and x = 1320 mm). It should be noted that the time axis starts at -200 µs for the two lower curves due to pre-triggering of the transient recorder.

The behaviour of the pellet acceleration and the pressure transients as described above is typical for firings with the fast valve at a pressure of 40 bar. However in some cases the breech pressure curve shows a pronounced pressure peek at t = 1600 µs where Fig. V.7 (x = -30 mm) shows a weakly peaked shoulder. As this pressure peak is believed to indicate the break-off pressure of the pellet, this variation indicates different degrees of adhesion of the pellet to the barrel from one shot to another. In cases where a pronounced peak at the breech pressure is observed, also an oscillatory behaviour is observed superimposing the decaying form of the acceleration as a function of distance in the barrel, Fig. V.6.

VI. RESULTS FOR ARC-HEATED ACCELERATION

The first results were obtained with only a limited amount of diagnostic equipment in operation. The following diagnostics were used: The optical pellet detectors, giving the muzzle speed and state of integrity of the pellet. The fast flash equipment fo. pellet photography. The PZ pressure transducer, indicating the pressure transient in the arc chamber. And finally the current shunt and voltage probe for recording of arc current and arc voltage.

It was decided not to mount the barrel with the light fibre and pressure transducer stations for the first runs, but only to use a smooth gun barrel. This decision was made partly in order to avoid the time consuming work in remounting this equipment while running-in the arc where dismantling of the setup is likely to be required and partly to see what change if any is caused by replacing a smooth gun barrel with one with holes and slits (for the light fibres and pressure transducers).

A new extrusion nozzle with a gun barrel of slightly different dimensions was used for the arc gun. The arc chamber was, as mentioned earlier, made so that it could also be used with the fast valve. Runs were made with the fast valve in order to ensure that good and unbroken pellets could be made with the new nozzle/barrel. In Fig. VI.1 are shown 6 photos of pellets made with a flash time of 20 ns.

The arc was driven by the interim 4-section power supply. The output resistor for each battery was 1 Ω and the output inductances for the four batteries were chosen to be 15, 30, 45 and 85 μH. Runs were performed with batteries fired in different sequences and with differing time delays.

Fig. VI.2 shows typical recordings for an arc firing. Curve a) shows the arc current and voltage time behaviour, curve b) shows the time behaviour of the signal from the PZ pressure transducer at the arc chamber, and curve c) is the signal from the optical pellet detector. The charging voltage of the power supply was 2.2 kV and the battery firing sequence was 85, 45, 30, 15 μH at times 0, 100, 150, 175 μs respectively. The H_2-propellent dose was 40 bar cm^3 at room temperature and the observed pellet velocity was 1380 m/s. In Fig. VI.2.a the current shows a double humped behaviour with a maximum peak value of about 1.3 kA and a total duration of about 700 μs. The arc voltage rises to about 2 kV in about 300 μs and jumps thereafter to a level around 700 V. The strong oscillations in the rising voltage occur at a frequency of around 100 kHz. The shape of the signal from the PZ pressure transducer (Fig. VI.2.b) indicates the time behaviour of the pressure in the arc chamber. The signal shows a maxium of ~ 24 mV at around 350 μs. If the former calibration factor of ~ 2 mV/bar is used this gives a peak pressure of ~ 12 bar. However, due to the mounting of the transducer in the outlet conical section of the arc chamber, the measurement is modified by the flow conditions for the propellent gas. Even if the actual pressure level in the arc chamber may not be determined from this measurement, the time behaviour of the signal indicates that the pressure is increasing only during ~ 200 μs. If a larger H_2-dose is applied the signal amplitude increases but the time behaviour remains unchanged and other sequence combinations tested, of the power supply sections, have so far given similar results.

Fig. VI.1.c shows the analog signal from the optical pellet detector, this is placed 400 mm from the muzzle. The signal indicates the passage of a whole pellet with a velocity of ~ 1380 m/s. The integrity of the pellet is also verified from the flash photo.

Fig. VI.3 shows the power input to the arc (b) and the arc resistance (c) as functions of time, obtained from the arc current/voltage curves (a). It is seen that a power peak of ~ 1.5 MW appears at around t ≈ 270 μs and that the resistance peaks at ~ 4 Ω around t ≈ 360 μs.

VII. CONCLUSIONS AND RECOMMENDATIONS

An experimental setup designed for a study of acceleration of 3 mm$^{\emptyset}$ pellets by an arc heated gas gun is described. All the subsystems of the setup, i.e. the cryogenic pellet forming part, the diagnostics, the automatic firing system, the data collection system and preliminary systems providing the accelerating pressure were tested. Experiments with full power supplied to the arc were not performed because of a delay in delivering of the final power unit. A few results of accelerating pellets with the arc heated gas were obtained during the tests. During these experiments with the interim power supply it was found that the pellets were acted upon by a high acceleration pressure only at the very beginning of its motion along the barrel. Although the velocities obtained are relatively low (~ 1500 m/s) the results are encouraging as they show that pellets can without disintegrating stand high acceleration pressures from arc heated gas. If by means of the final power supply such high acceleration pressures acting on the pellets can be maintained as they move along the barrel, then velocities well above 2 km/s would certainly be obtained.

It is therefore recommended that the work should be continued under a new art-14 contract in order that the original aim: to study the potential of an arc heated gas gun system to accelerate pellets to velocities well above 2 km/s, could be fulfilled.

VIII. ACKNOWLEDGEMENT

Dr. P. Kupschus has acted as JET Project Monitor during this work. The authors are grateful for his interest in the work and for many of his suggestions for improvements.

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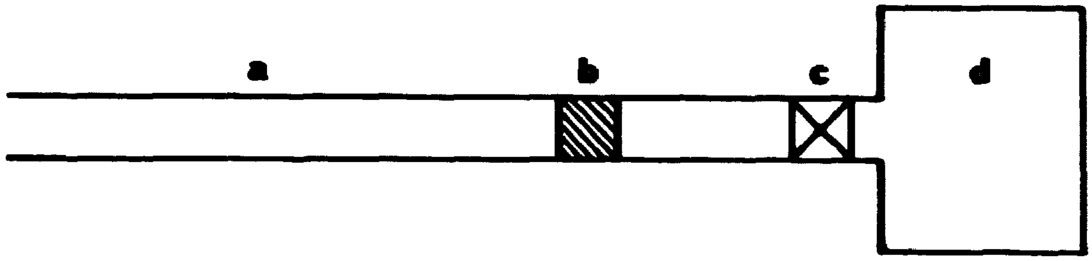


Fig. I.1. Schematic drawing of simple gas gun accelerator.

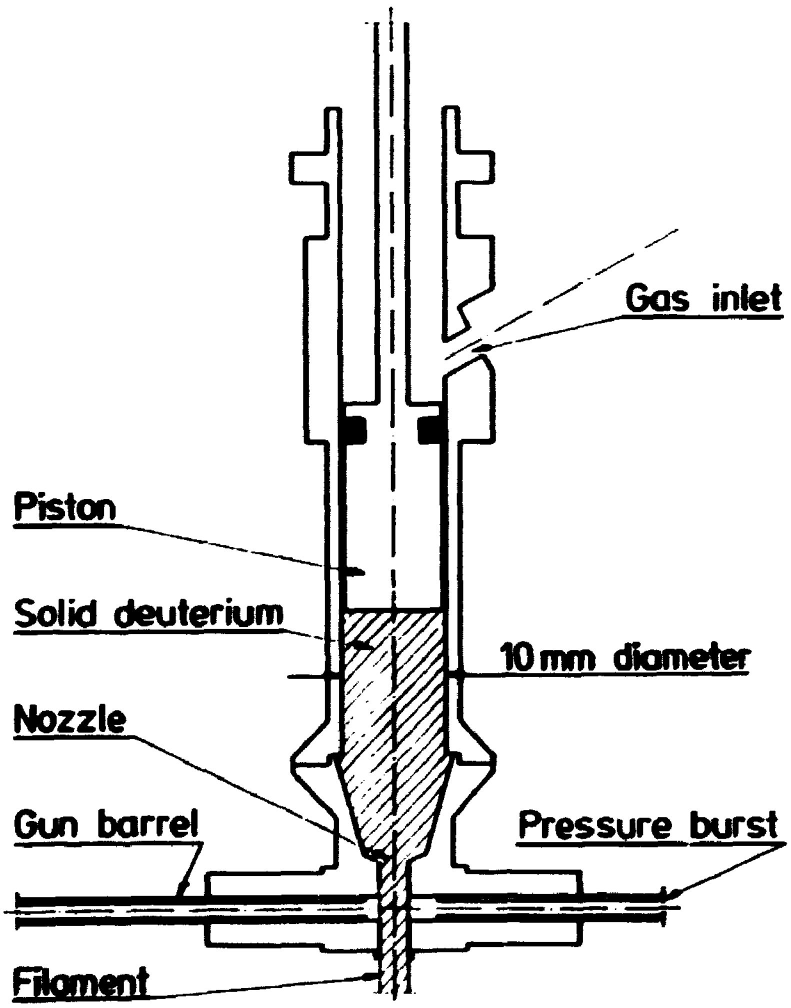


Fig. II.1. Schematic drawing to illustrate extrusion of solid D_2 and loading of pellet.

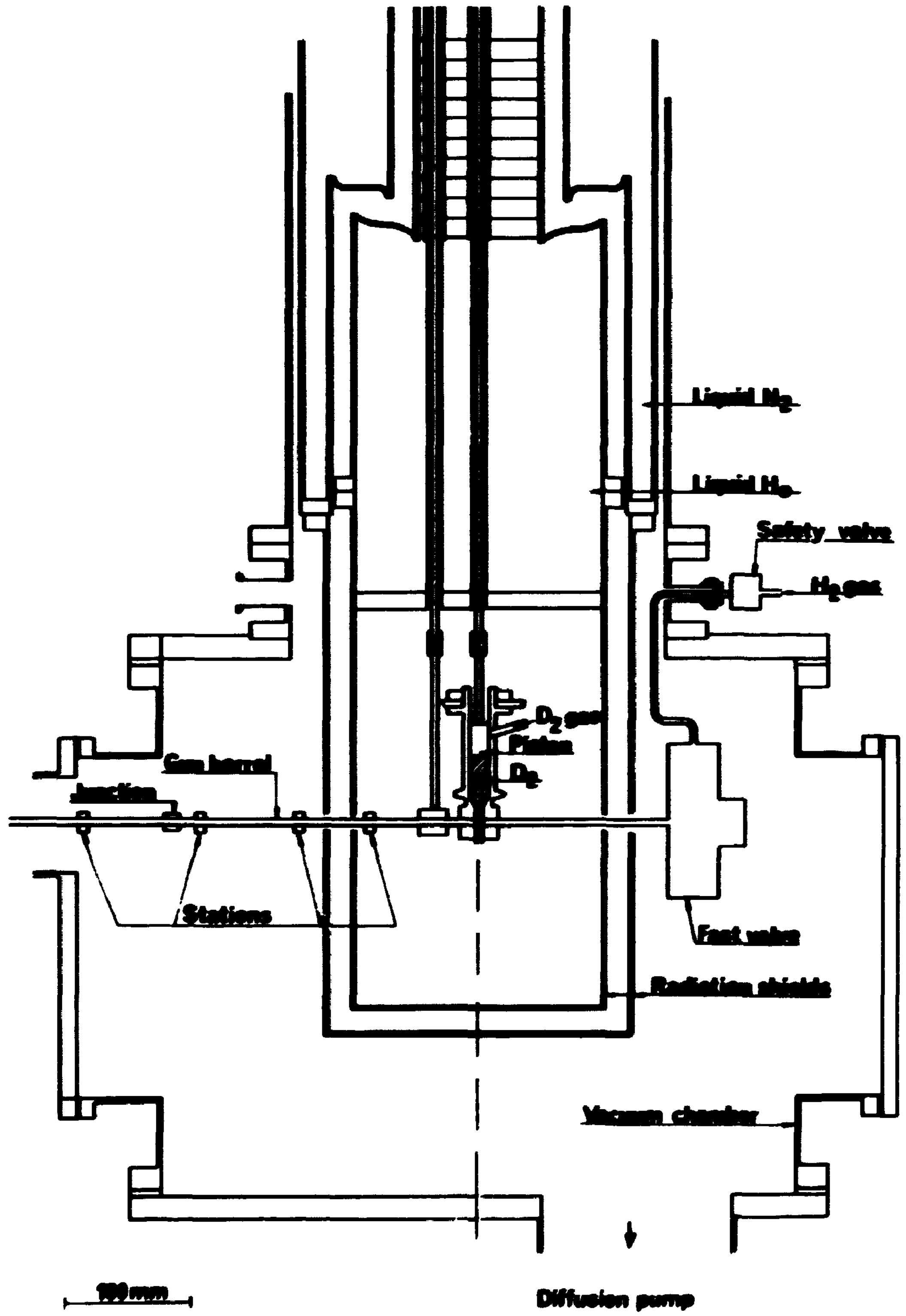


Fig. II.2. Schematic drawing of the cryogenic part of the gun.

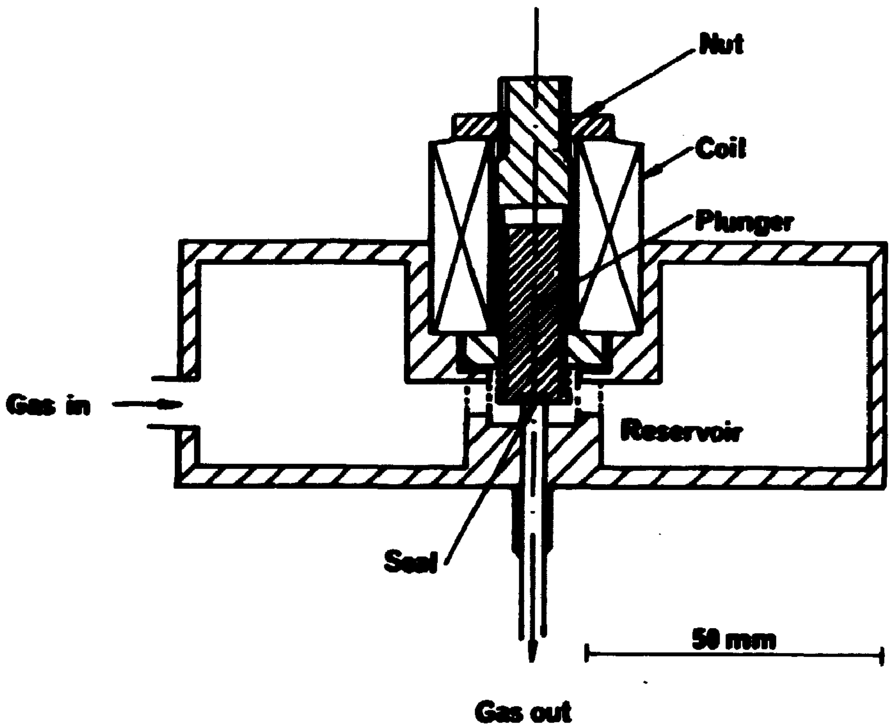


Fig. II.3. Schematic drawing of the fast valve.

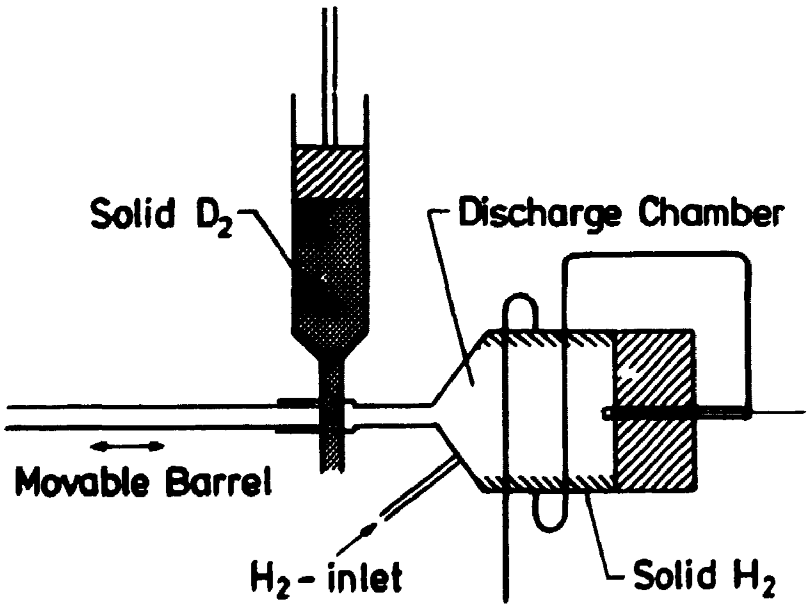


Fig. II.4. Schematic drawing to illustrate the principle in arc acceleration.

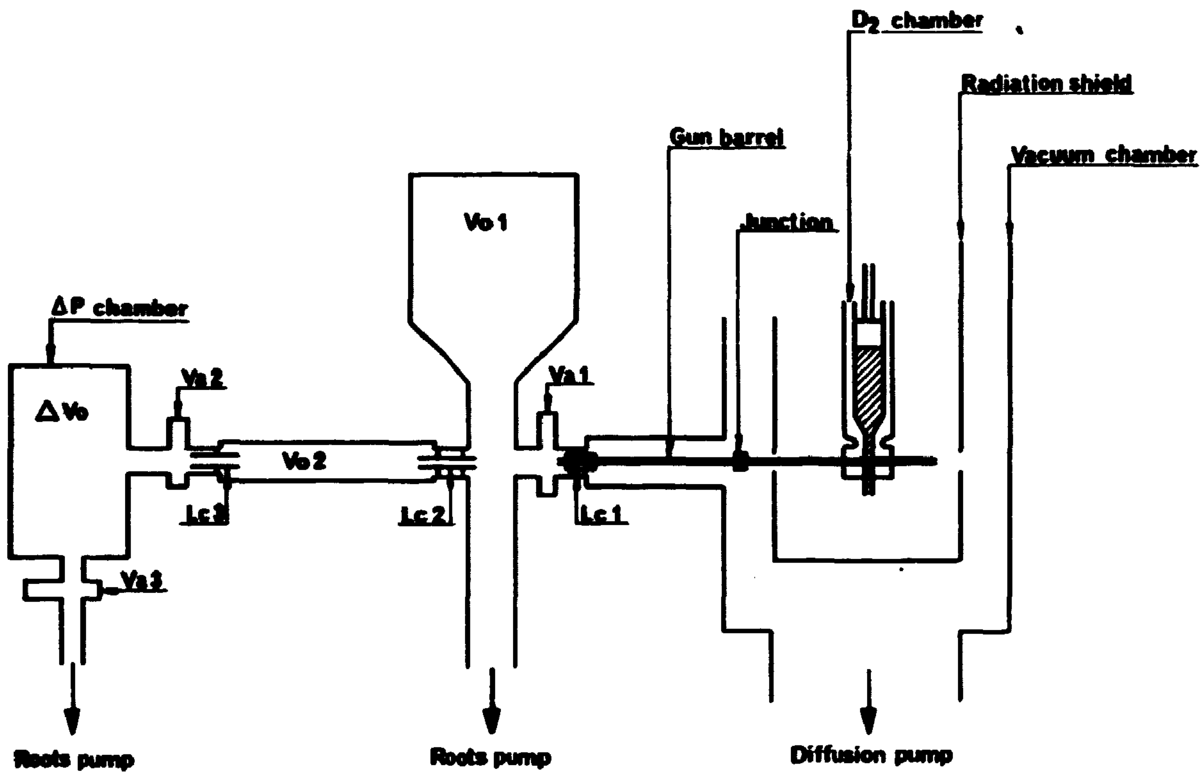


Fig. II.5. Schematic drawing of the cryogenic vacuum system and the outer vacuum system.

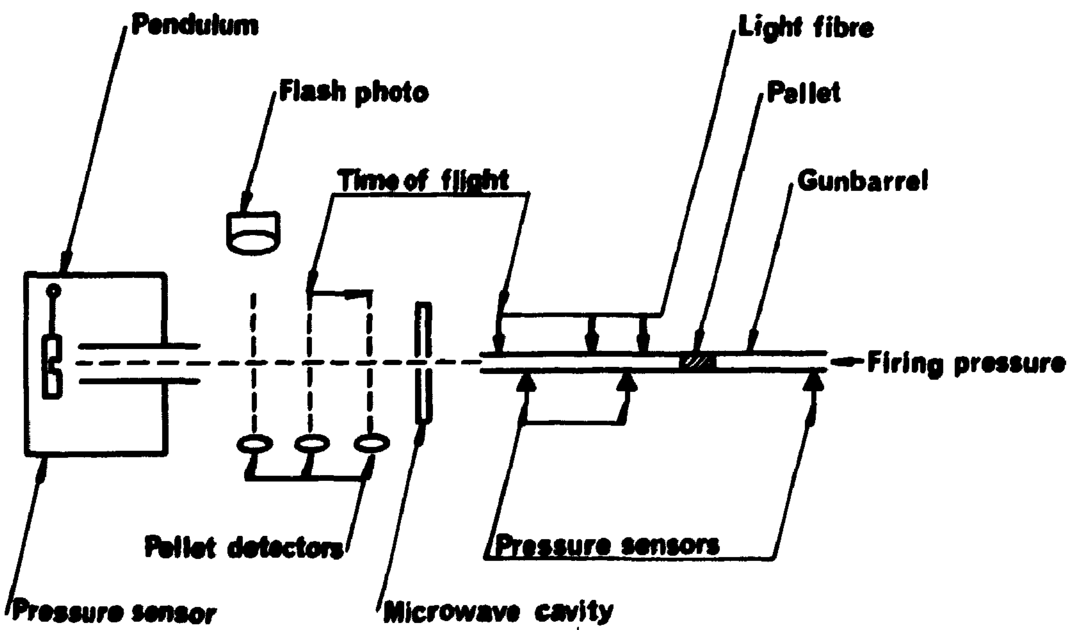


Fig. III.1. Schematic drawing to illustrate the diagnostic methods used.

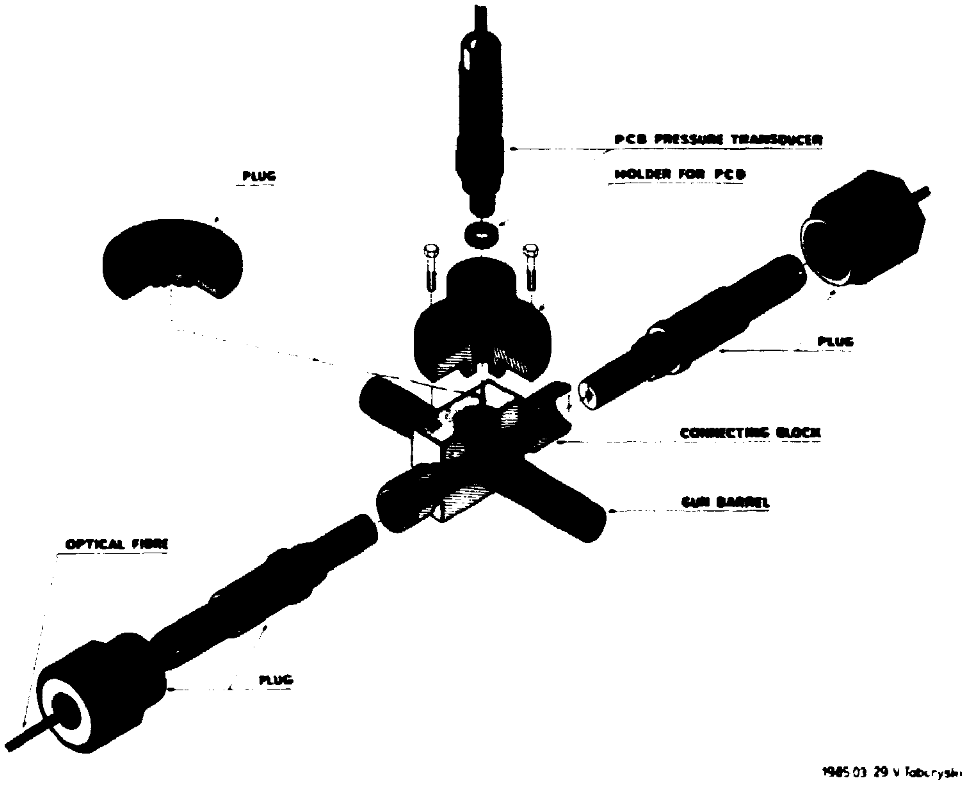


Fig. III.2. Exploded view of block with optical fibres and PCB pressure transducer.

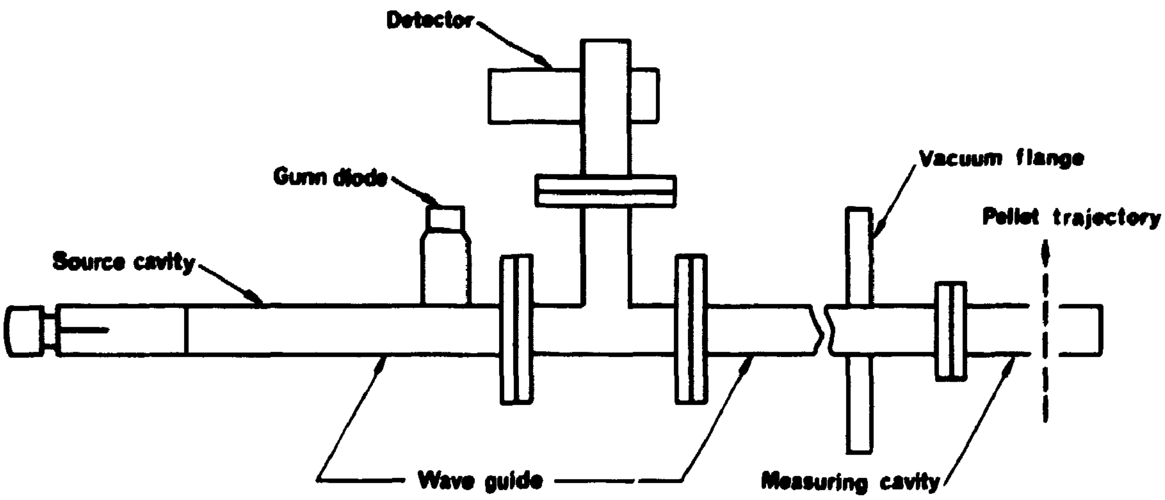


Fig. III.3. Schematic drawing of microwave cacity for pellet mass measurement.

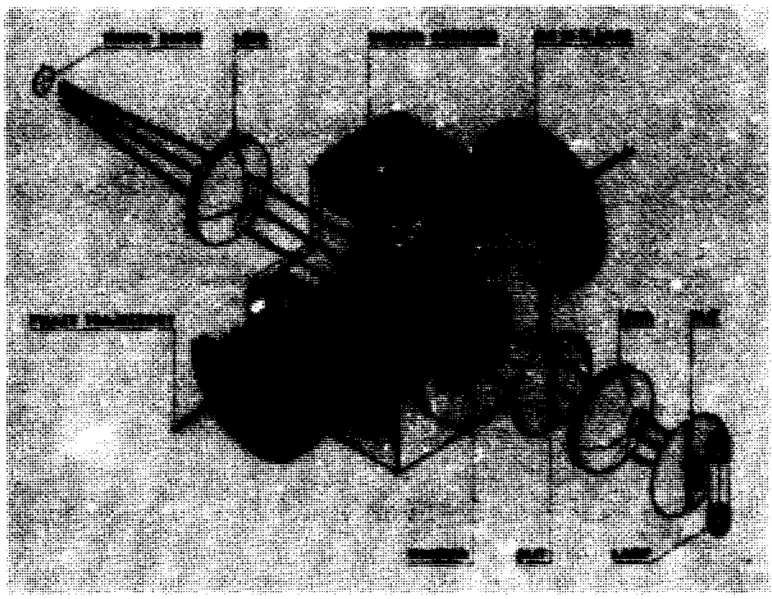


Fig. III.4. Exploded view of optical pellet detector.

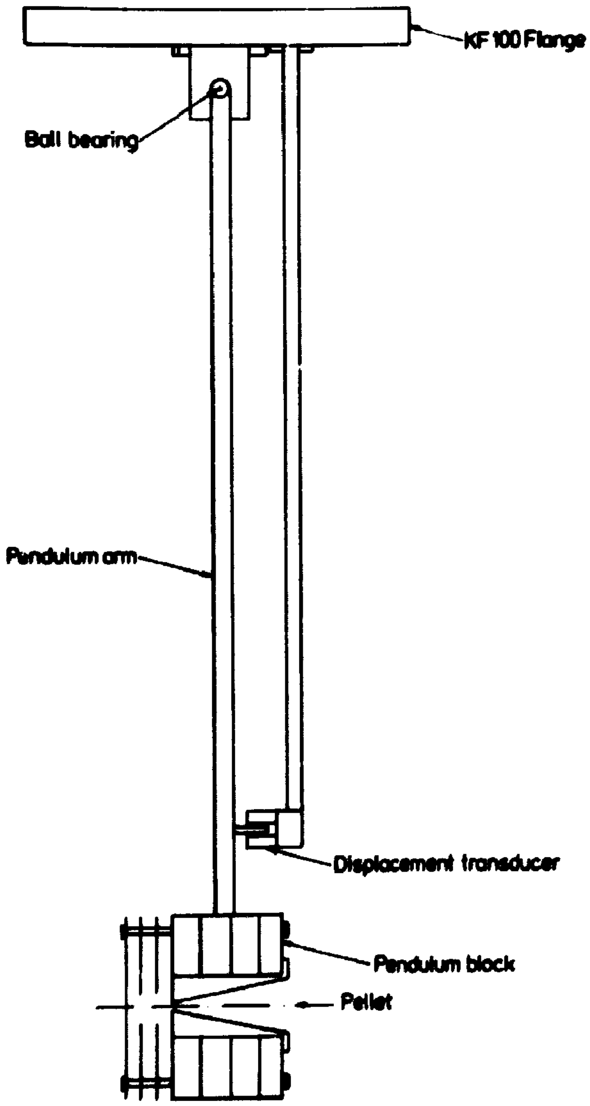


Fig. III.5. Schematic drawing of pendulum for pellet momentum measurement.

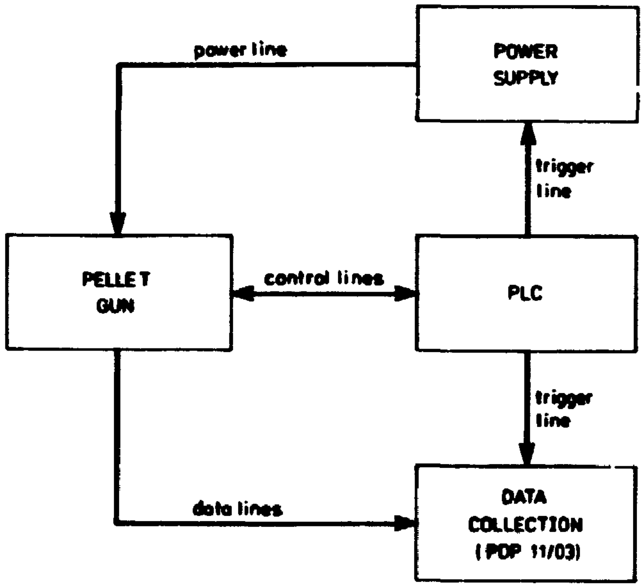


Fig. IV.1. A schematic diagram of the automatic firing system.

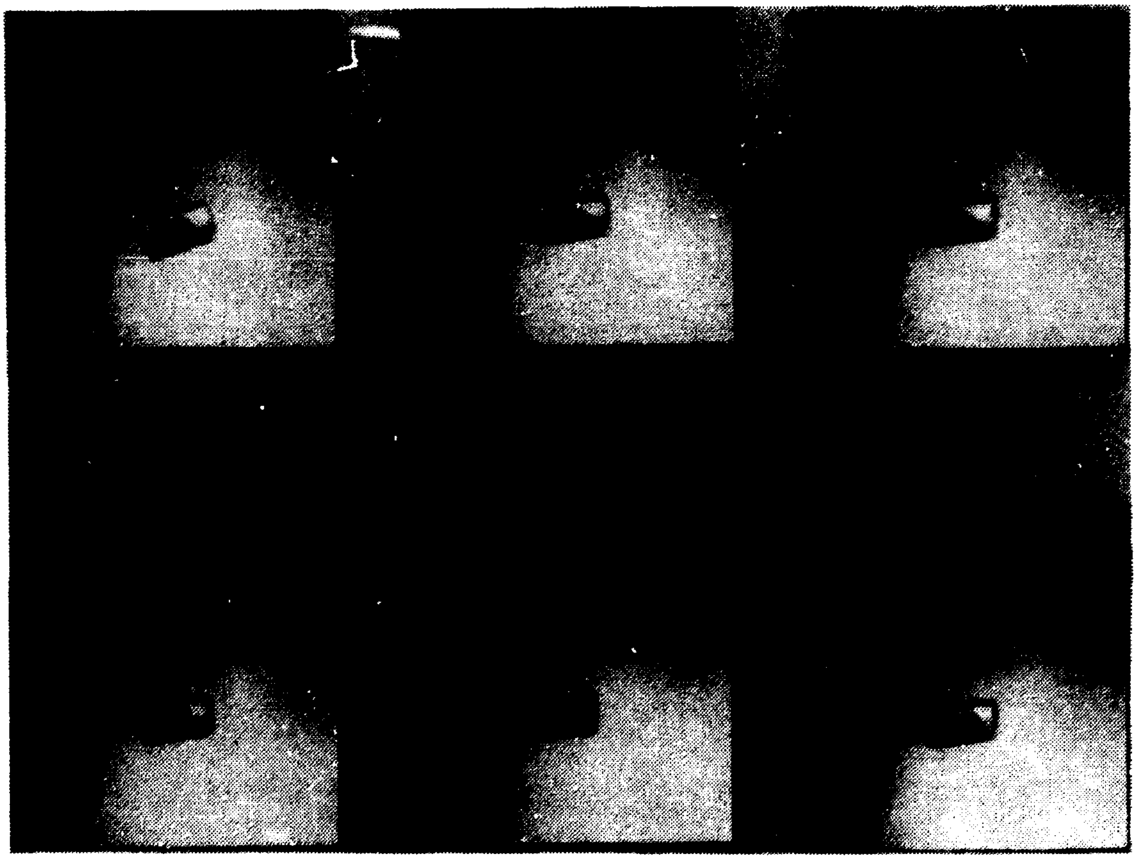


Fig. V.1. Flash photographs of 3.2 mm o. d. pellets. Flash time 200 ns.

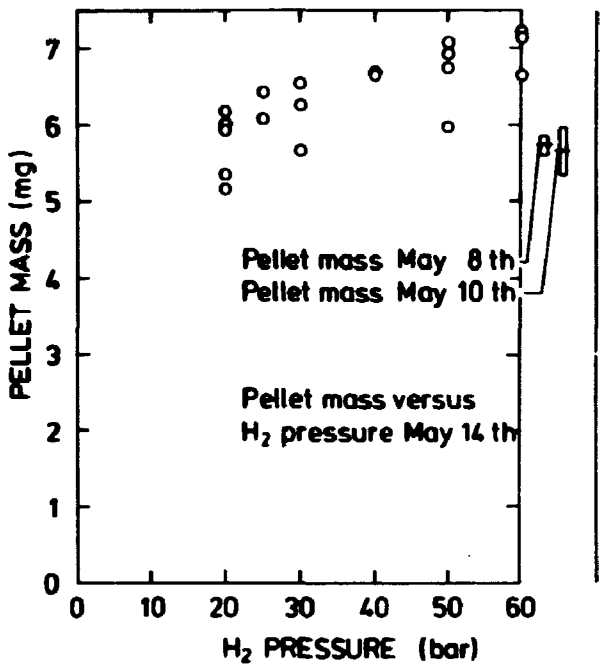


Fig. V.2. Pellet mass deduced from pressure increase in ΔP chamber versus propellent gas pressure for a too large inlet of propellent gas. Also shown are pellet masses from two earlier runs.

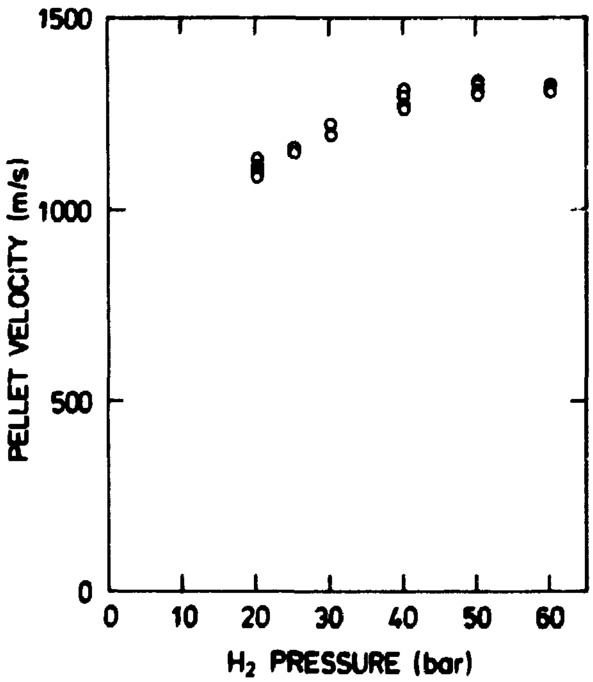


Fig. V.3. Pellet velocity versus propellent gas pressure.

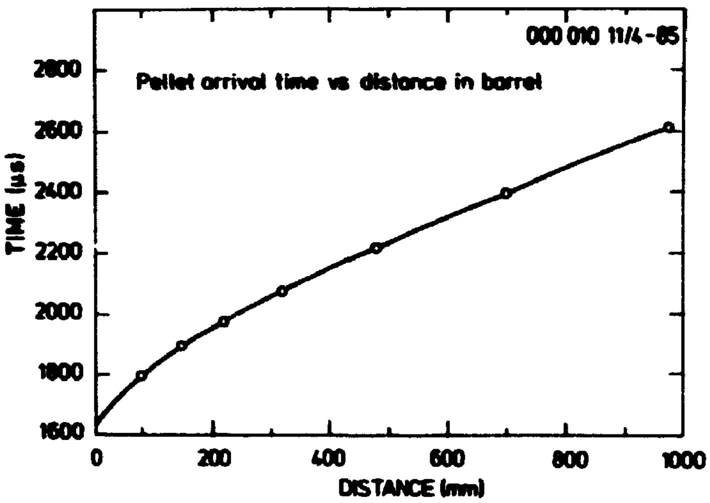


Fig. V.4. Pellet arrival time versus distance in barrel.

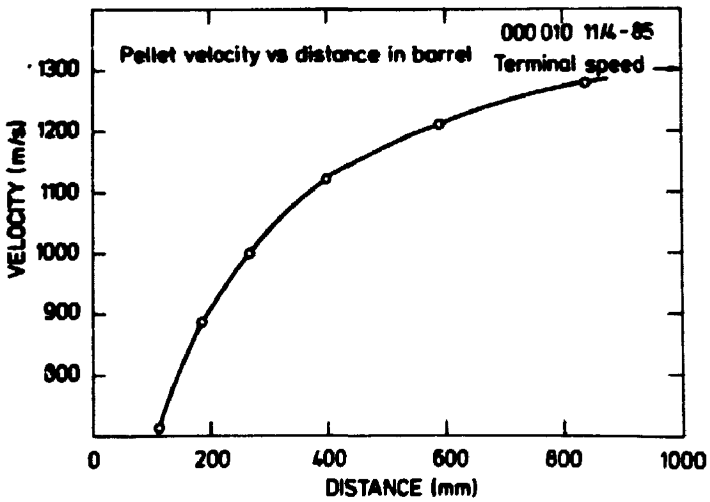


Fig. V.5. Pellet velocity versus distance in barrel.

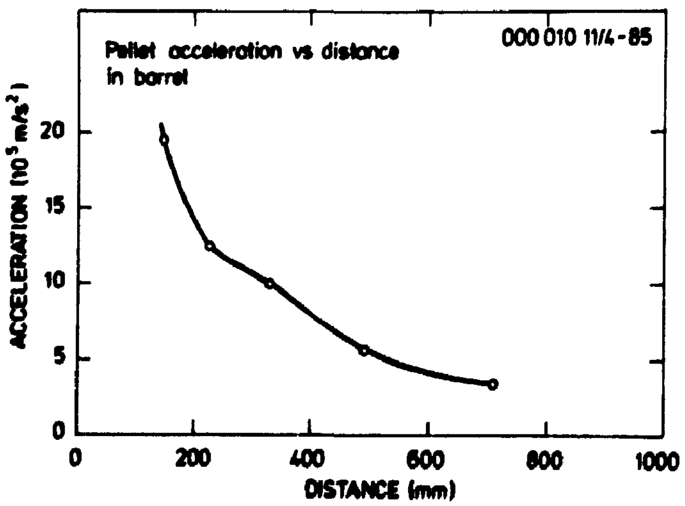
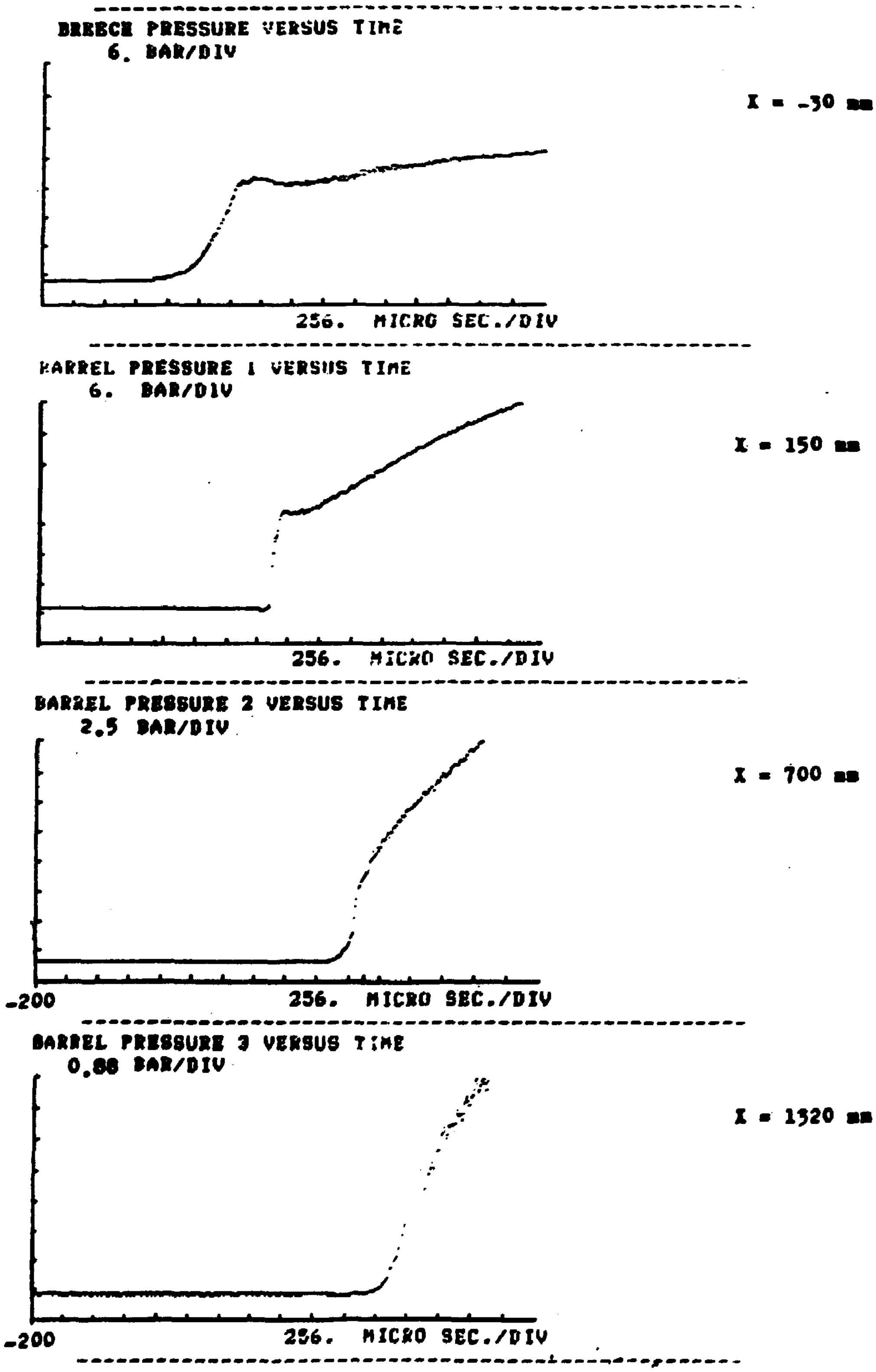
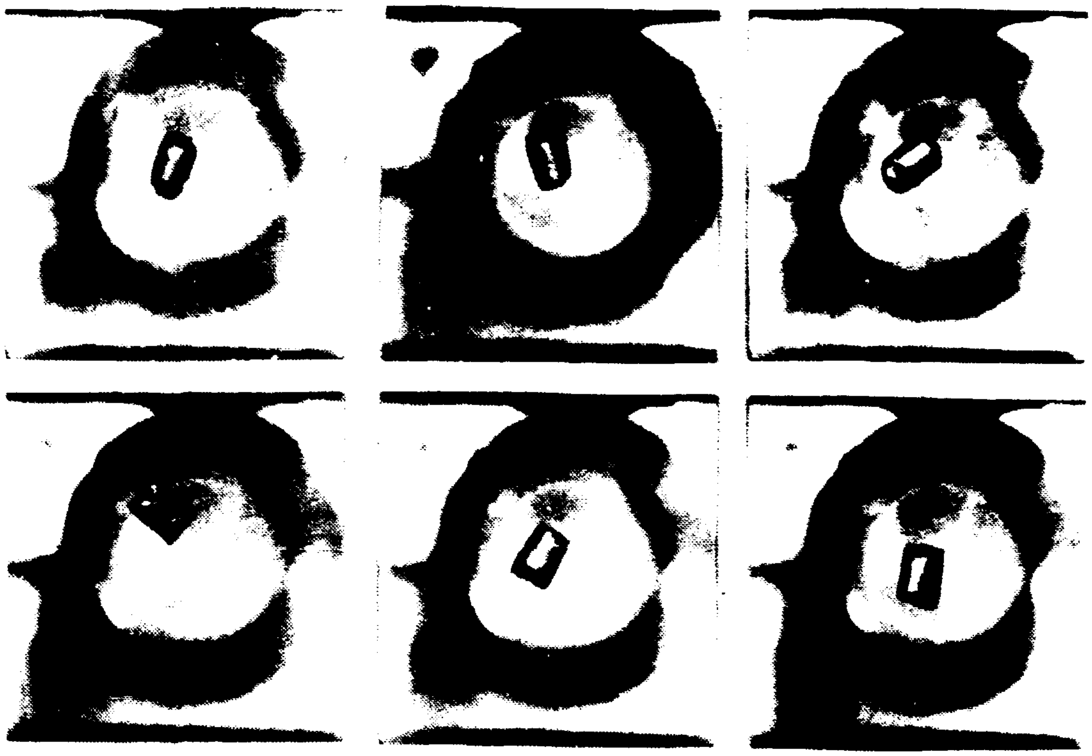


Fig. V.6. Pellet acceleration versus distance in barrel.



<u>Fig. V.7</u>. Pressure transients at different positions in the barrel.



1985-06-11 → ~1100 m/s

Fig. VI.1. Flash photographs of 3.[illegible] mm o.d. pellets. Flash time 20 ns.

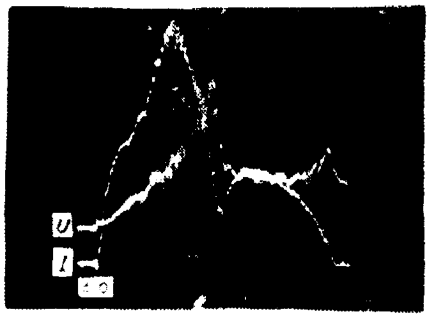
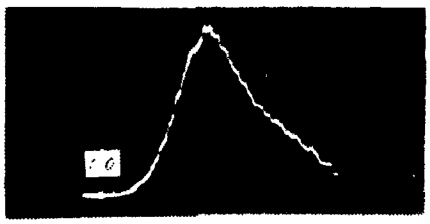
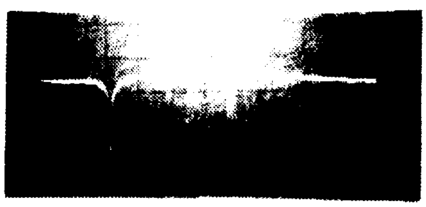


Fig. VI.2. Data from an arc acceleration. Arc current (I) and voltage (U) versus time. I: 200 A/div. U: 500 V/div. Time base: 100 [illegible]s/div.



Signal from ceramic pressure transducer at arc chamber. Signal: 5 mV/div. Time base: 100 [illegible]s/div.



Signal from optical pellet detector. Signal: 1 V/div. Time base: 20 [illegible]s/div.

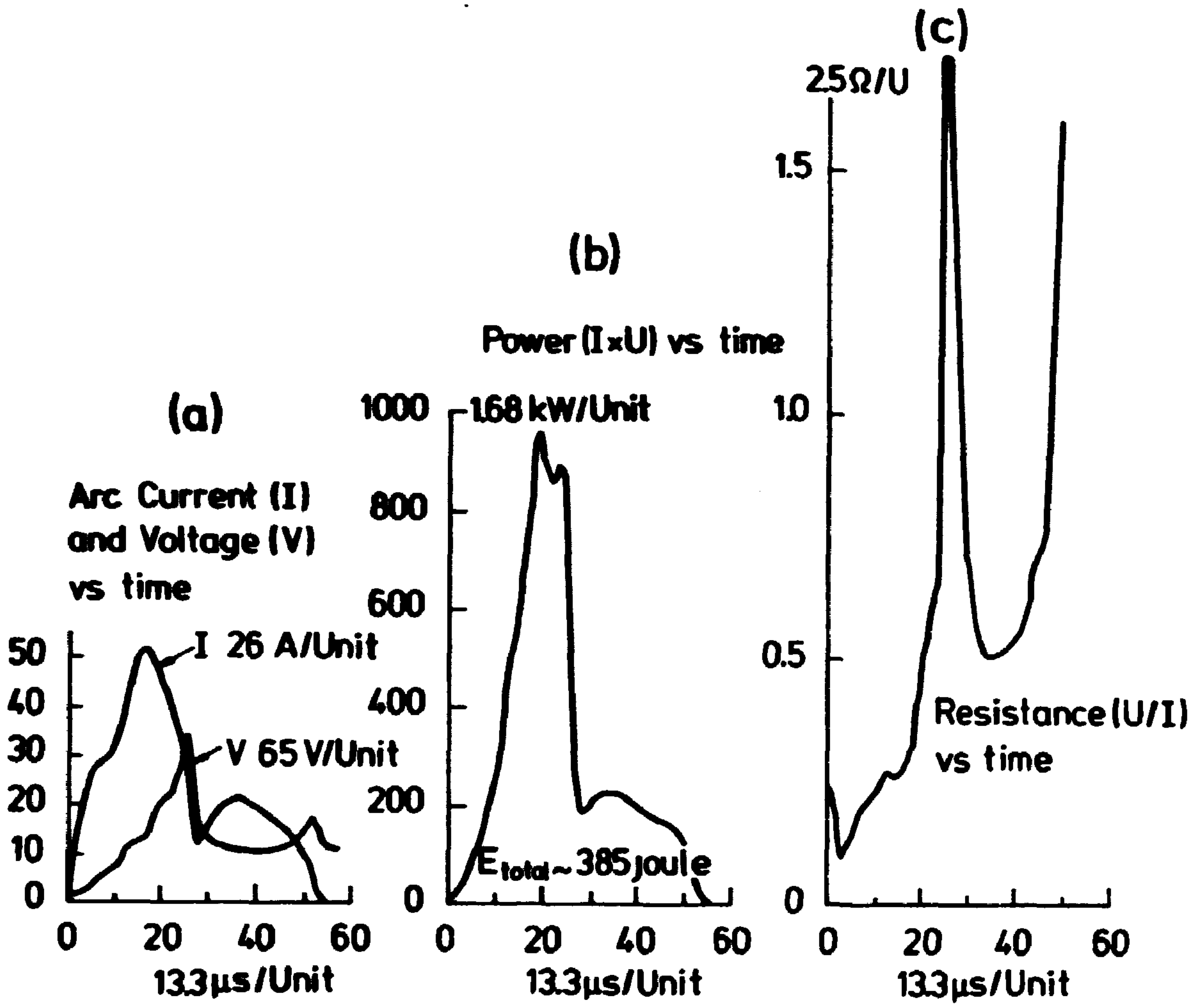


Fig. VI.3. Arc characteristica.

a) Arc current and voltage.

b) Power input to arc computed from figure VI.2.

c) Resistance of arc computed from figure VI.2.

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INVESTIGATION OF PELLET ACCELERATION BY AN ARC HEATED GAS GUN*
An Interim Report on the Investigations carried out to 31 August 1985

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Abstract

Deep penetration of pellets into the JET plasma may prove to be a useful tool for density and profile control. In JET deep penetration will require pellet velocities and sizes above those obtained so far. An experimental setup designed for a study of acceleration of 3 mmØ pellets by an arc heated gas gun is described. The aim of the work is to obtain pellet velocities well above 2 km/s. To obtain this aim will require a much more powerful power unit than the one that was available for the present work. Only a few results, obtained mostly during testing of the various parts of the setup, are presented. Although the obtained velocities are low (~ 1500 m/s) the results are encouraging because they demonstrate that pellets can stand a high acceleration pressure without disintegrating. With a suitable power supply which can maintain this high acceleration pressure as the pellet moves all the way through the barrel, velocities above 2 km/s would certainly be expected.

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